The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction

Investigation on The Seismic Behavior of Steel MRF with Shape Memory Alloy Equipped Connections

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Abstract

Shape Memory Alloys (SMA) are among the new passive control devices that have gained a large attention due to its inherent features, i.e., recovering the induced residual strains upon unloading (superelastic effect) or by heating (shape memory effect). In this work, the seismic behavior of a set of steel structural models with different number of stories and eccentricities equipped with a type of fixed SMA connections is investigated. Considering an existing SMA connection model in austenite phase, the related moment-rotation behavior is verified through numerical simulation. Then, extensive nonlinear dynamic analyses are performed using a number of 3, 6, 9, and 12 story structural models with 0, 5%, 10%, and 15% eccentricities subjected to different bi-directional earthquake components. The PGA of the earthquake records is scaled to 0.4g and 0.6g to examine the energy dissipation capability of the SMA materials. Similar analyses performed using the same set of structural models, but with all beam-to-column connections equipped with SMA connections. The obtained results indicate that while the reduction in drifts of the SMA equipped models with respect to the fixed connection models was not noticeable, their base shears were considerably reduced. The OpenSees program is used for modeling of the connections with SMA materials and performing the numerical analyses.

Keywords: Passive control system; Shape memory alloy (SMA); Superelasticity; Steel moment resisting frame; dynamic response.

1. INTRODUCTION

The occurrence of destructive Earthquakes and the resulting damages has clearly shown the need for more advanced equipments to protect the building structures against earthquake excitations. After the

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introduction of Shape Memory Alloys (SMA) and their specific mechanical features such as superelasticity (Greninger and Wang 1938; Castleman and Motzkin 1981), the feasibility of its application for earthquake mitigation was investigated by many researchers and engineers. Many families of shape memory alloys such as AuCd, CuZn, NiTi, etc. have been introduced for different applications. Experimental studies demonstrate that these materials show a unique phase transformation by changing in external stress or ambient temperature.

In general, the austenite phase of these materials is stable in high temperature and low stress levels, while the martensite phase is stable in low temperature and high stress levels. Any SMA element such as a rod is austenitic at temperatures above A_f (austenite finish temperature). In this phase, when this rod is subjected to a tensile loading, at a particular tensile stress and constant ambient temperature, phase transformation will start from austenite to martensite which is called forward transformation. From the beginning of transformation until the end of it, strain in SMA rod increases whereas the stress remains almost constant. During unloading, since the martensite phase is unstable in temperature higher that A_f without external stress, the reveres transformation from martensite to austenite initiates. If the material temperature remains larger than A_f, the residual strain in rod will approach to zero upon unloading. This behavior that leads to dissipation of external imposed energy and then recovery of the residual strains is call superelasticity (Figure 1).
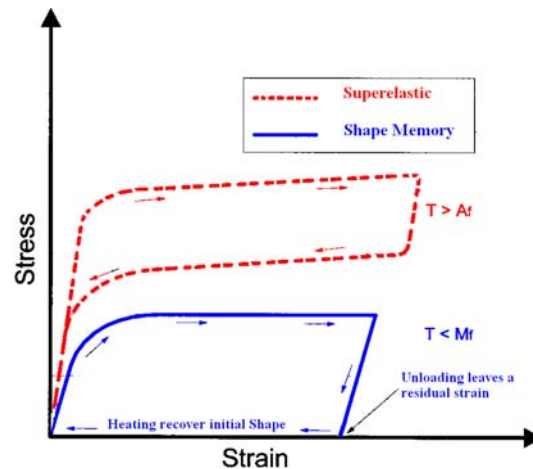

Figure 1: Stress-strain behavior of austenite and martensite SMAs

If material temperature becomes lesser than A_f, some part of martensite will not change to austenite, therefore, the strain will not recover completely which can be resolve by heating the material. This phenomenon is call semi-superelasticity. In temperatures below M_f (martensite finish temperature), the alloy is martensitic and possess shape memory effect (Figure 1). In this temperature, SMA do not recover its residual strain automatically, but, restoring the initial shape is possible by heating the material over A_f. Among many families of alloys, NiTi is often preferred for possible use in actuators and other passive control devices.

2. SMA CONNECTION

A new application of SMA is the beam-column connections equipped with SMA in steel moment resisting frames. A new class of partially restrained connections using NiTi in martensitic form that was introduced in 2004 (Ocel et al. 2004), exhibited acceptable performance. This connection is consisted of four NiTi SMA bars connecting beam flanges to column flange which can transfer moment. Experimental results have proved their ability to be utilized in partially restrained connections.

Shape memory alloys in austenite phase are also applicable in beam-column connections. Ma et al. in 2007 investigated a new connection consisting of an extended end-plate with SMA bolts, continuity plates, beam flange ribs and web stiffeners shown in Fig.2 (Ma et al. 2007). In this paper, this beam-column connection model is selected to be simulated by OpenSees program.
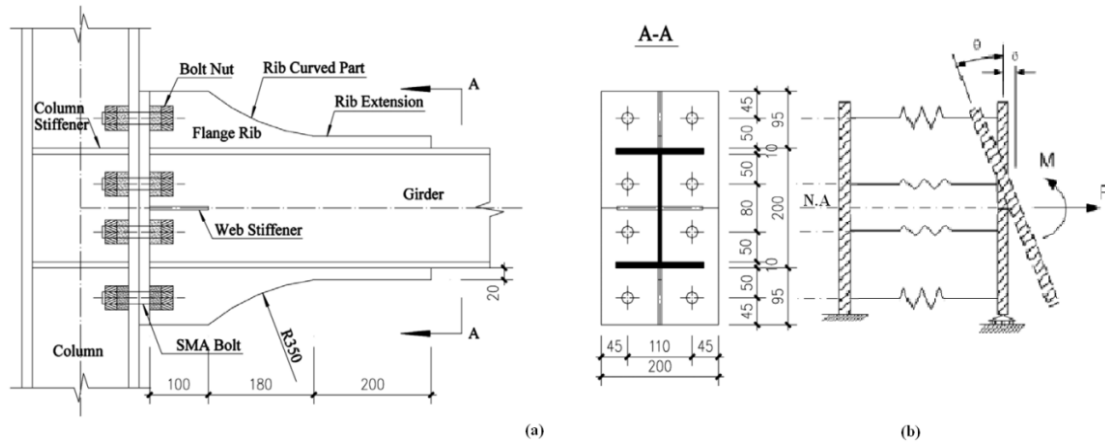

Figure 2: SMA connection. (a) Diagram (Ma et al. 2007). (b) Fiber Modeling in OpenSees

Auricchio's model for simulating SMA superelastic behavior is shown in Fig. 3.a(Auricchio and Sacco 1997). In this Fig. σ_s^{AS} and σ_f^{AS} are starting and final stress in martensite forward transformation, and σ_s^{SA} and σ_f^{SA} are starting and final stress in austenitic reverse transformation which are equal to 375, 430, 208, and 158 MPa in SMA bolts of Ma's connection. Bolts have 16mm diameter with a modulus of elasticity, E, equal to 275790kg/cm^2.
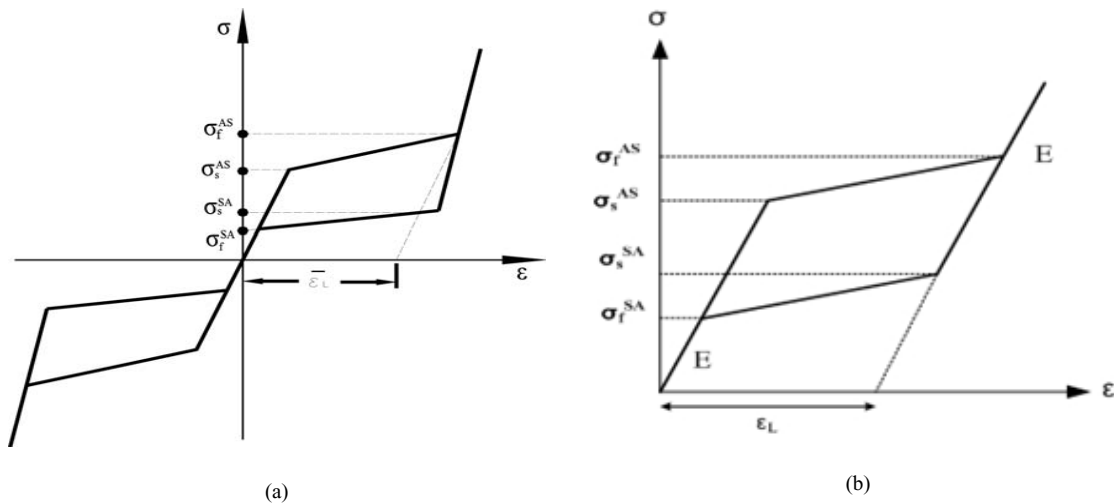

Figure 3: Schematic stress-strain SMA behavior. (a) Auricchio's model in ANSYS (Ma et al. 2008). (b) Fugazza's model in OpenSees

OpenSees use Fugazza's model for simulating SMA superelastic behavior shown in Fig. 3.b. (Fugazza 2003). In fact, this model is a version of Auricchio's model with similar modulus of elasticity in forward and reverse transformation, but performs faster in dynamic analysis. In the proposed connection, SMA bolts have eccentricity about beam's neutral axis. Therefore, the moment is transferred through a force

couple due to tension in the SMA bolts. No compression occurs in SMA bolts, since they have been pretensioned. Also, based on Ma's model, the SMA bolts do not experience any shear.

According to the details discussed above, the fiber modeling approach in OpenSees is considered. Each SMA fiber is assigned the "uniaxialMaterial SMA" with the respective mechanical properties. Finally this section is assigned to a "zeroLengthSection" element to act like a rotational spring at beam-column joints.

3. STRUCTURAL MODELING

A number of 3-D steel moment resisting frame buildings with 3, 6, 9, and 12 stories, and 0, 5%, 10%, and 15% eccentricity, each floor 3 meters high, are considered to investigate the performance of SMA equipped connections in reducing their seismic response. The structural plan consists of two and three spans in X and Y directions respectively, with each span 5 meters long. Dead and live loads are considered to be 600 kg/m^2 and 200 kg/m^2 respectively, with steel yield and ultimate stresses equal to 2400kg/m^2 and 3600kg/m^2 respectively. The structural members are designed to have stress ratios in the range of 0.7 to 1.1 under AISC-89 design load combinations so that the proportioning can be considered nearly optimized. Also, drifts were not controlled in order to let the structures display complete nonlinear behavior under earthquake excitations.

The Northridge, Loma Prieta, Big bear, Kobe, ChiChi, Duzce, and Tabas earthquakes which have been recorded on soil type S$_D$ and scaled to 0.4g and 0.6g are considered for nonlinear dynamic analyses. The resulting inter-story drifts, base shear, moment-rotation behavior of connections, and residual strains for both set of regular and SMA equipped structural models were evaluated to investigate the efficiency of utilizing this new connection.

4. NONLINEAR DANAMIC ANALYSIS OF STRUCTURAL MODELS

In order to compare the dynamic performance of buildings with rigid and partially restrained steel frame with SMA connection, extensive nonlinear dynamic time history analyses was performed using the seven earthquake records scaled to 0.4g and 0.6g .

The most significant change in these two set of structural models was the big shift in the first period of buildings with SMA connections. Periods in primary structures were 0.694, 0.874, 1.169, and 1.502 for 3, 6, 9, and 12 story buildings respectively that changed to 1.991, 2.673, 4.075, 6.041 seconds for the same structural models with SMA connections. Due to significant change in period of structures with SMA connections, their acceleration spectral amplitudes reduced noticeably. Ignoring the drift limitation in the design process was the main reason for this period change.

Contrary to the expectations, the drifts were not decreased due to extra ductility imposed to the SMA equipped models by replacement of rigid connections with SMA ones. Average inter-story drifts among seven pairs of earthquakes are shown in Figs. 5 to 8. In each figure, left, middle, and right lines are inter-story drift in X, Y, and XY (exact drift using SRSS combination of drifts in X and Y directions) directions, respectively.

Inter-story drifts in structures with different eccentricities differ slightly with symmetric structural models. Therefore, eccentric structure's drifts are not shown here.

Figures 6, 7, and 8 show inter-story drifts in 6, 9, and 12-story buildings respectively. In all cases, drifts in Y direction are more uniform than X direction due to larger number of columns and thus SMA connections in that direction. Also, more tributary gravity loads are assigned to the beams in Y direction. That resulted in more tension in upper SMA bolts in connections which produce larger hysteresis loops, thus enhancing the capability of dissipating the external seismic input energy through these connections.

Due to period elongation in SMA equipped models, and the related reduction in their acceleration response amplitude, significant reduction is resulted in the base shear force of those models. According to the results, the base shear decreases in structures with SMA connections when eccentricity increases that

is caused by increase in their fundamental period of vibration. Although usage of Ma's SMA connection model could not in general reduce the inter-story drifts in regular building, the residual displacements of the structural systems are decreased.
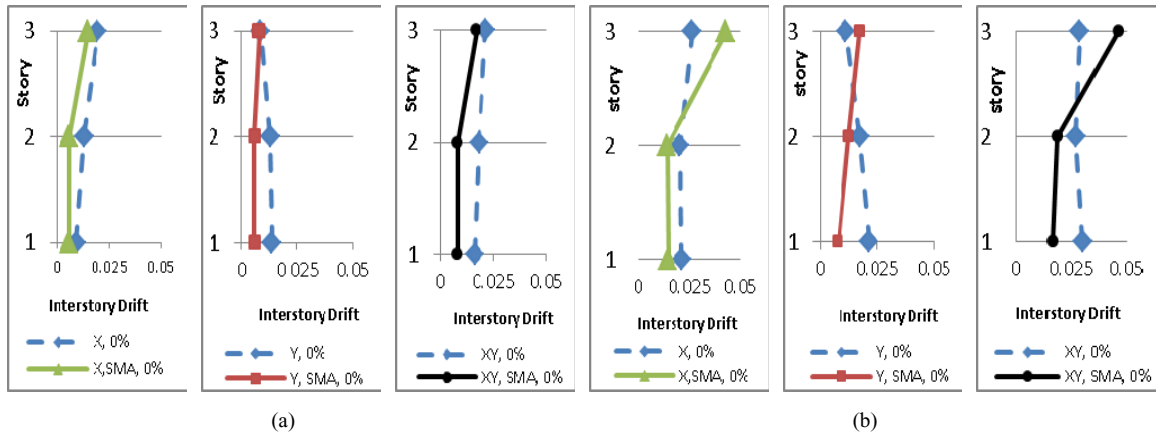
Figure 5: Inter-story drifts for 3-story building at (a) PGA=0.4g, (b) PGA=0.6g
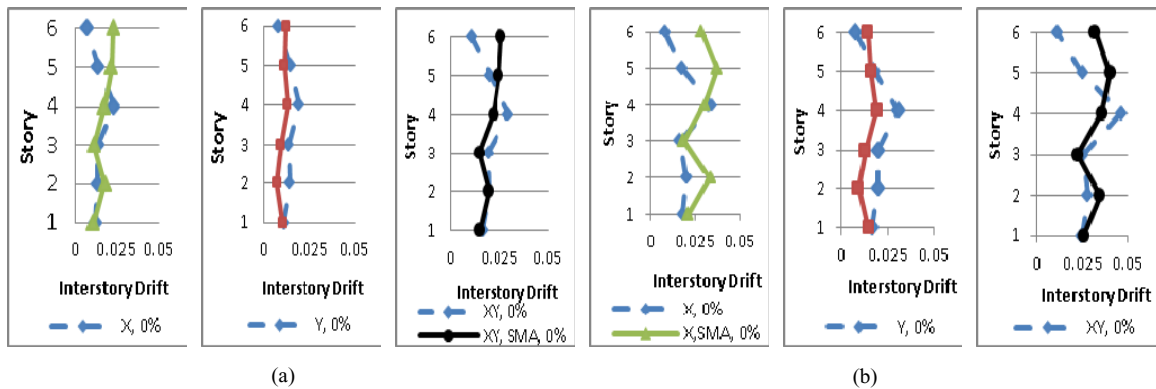
Figure 6: Interstory drifts for 6-story building at (a) PGA=0.4g, (b) PGA=0.6g
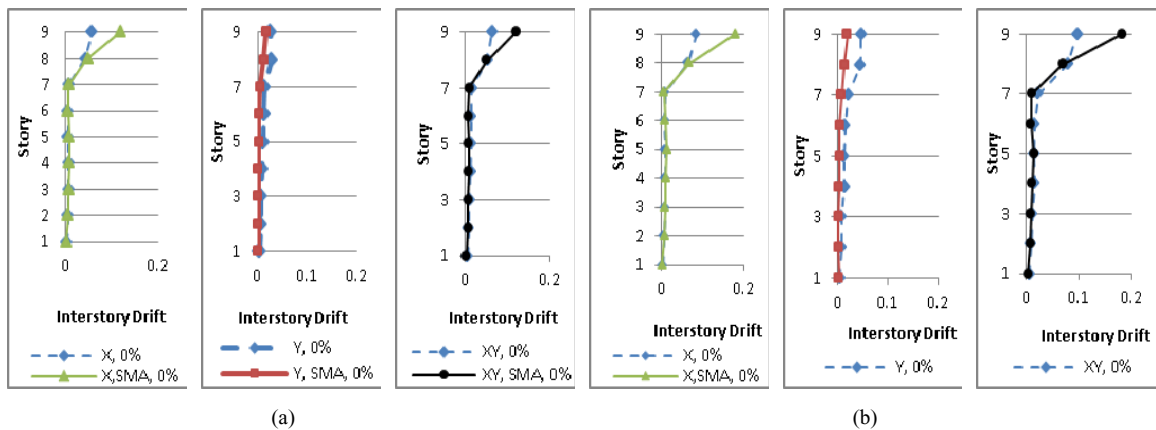
Figure 7: Inter-story drifts for 9-story building at (a) PGA=0.4g, (b) PGA=0.6g
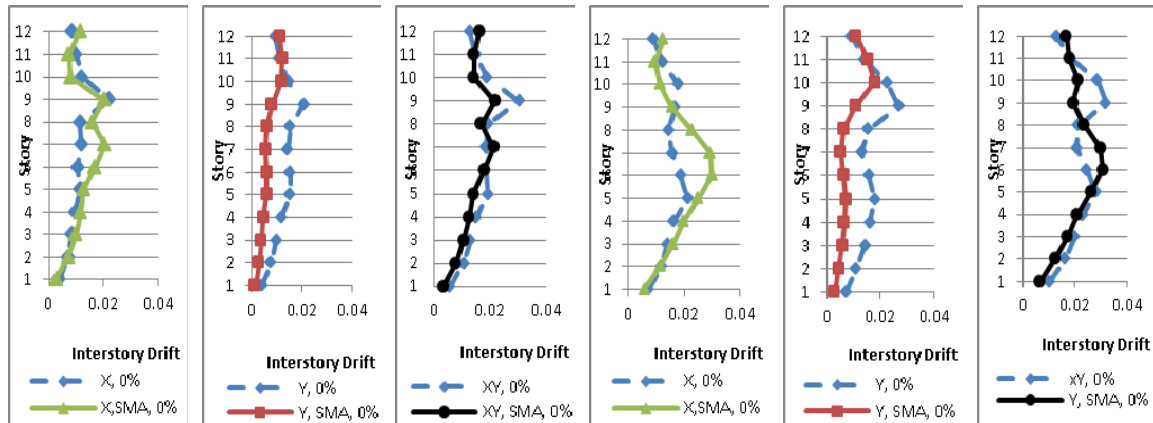
Figure 8: Inter-story drifts for 12-story building at (a) PGA=0.4g, (b) PGA=0.6g

5. CONCLUSION

According to the results obtained using Ma's SMA connection, application of SMA connection in all the beam-to-column connections of any structural model cannot guarantee reduction in inter-story drifts as this connection makes the buildings more ductile However, that would lead to a reduction in base shear force of those models. On the other hand, the residual displacements would definitely reduce due to superelastic feature of SMA materials. Also, SMA equipped connections cannot produce a noticeable change in lateral displacements of regular structures with small eccentricities more than symmetric ones. In general, Fugazza's model for SMA materials cannot include all the behavior change caused by different parameters in SMA material such as temperature change.

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